MOVING THE WORLD WITH SURFACE-MICROMACHINING (ONE MICROGRAM AT A TIME)

Abstract:

Surface-micromachining is the process whereby miniature mechanical devices, both sensors and actuators, are made using the same manufacturing technology which has made the integrated electronic circuit so successful. The first demonstration, almost 30 years ago, of a surface micromachined device was the Resonant Gate Transistor by Nathanson, Newell, Wickstrom, and Davis [1] which consisted of a transistor with a free-standing metal cantilever beam as the transistor gate. Over a dozen years ago, the first description of polycrystalline silicon (polysilicon) surface micromachining was given by Howe and Muller [2]. The years since then have yielded numerous prototypes for sensing devices and, recently, the first marketable sensors [3]. However, a surface-micromachined device doing work on its environment (actuation) has remained more elusive. Phenomena which are usually inconsequential in the normal scale of things become indomitable at sub-millimeter dimensions. Surface tension, which allows a mosquito to walk on water, is one notorious example. These phenomena affect "normal" friction and wear, which, although adequately controlled in large-scale machinery, must be re-examined at a fundamental level when considering micro-devices. Despite these issues, microactuation with surface-micromachined devices finally is taking hold and promises to impact our lives in fascinating ways.

Polycrystalline Silicon Surface Micromachining

The scope of fabrication techniques and the types of devices, both sensing and actuating, categorized as Microelectromechanical Systems (MEMS) has widened dramatically in the past few years. This is clearly indicated by the proliferation of publications by an increasing number of groups in the MEMS conferences and journals [4]. Many people regard this diversity of fabrication techniques as a primary reason why MEMS has failed to revolutionize our lives. Discussion of this and other reasons why MEMS has not been as successful as the Integrated Circuit (IC) were addressed in an earlier Solid State Technology article[5].

The discussion in this article will briefly cover fascinating developments in microactuators which produce rotational output and which are fabricated by polysilicon surface micromachining. This technology is closely related to IC-type fabrication and

microactuators which produce rotational output have been one of the most challenging and tantalizing research topics in MEMS. Recent advancements, including some at Sandia National Laboratories, finally provide promise that rotational microactuators known as micromotors or microengines may find their way into commercial applications in the near future.

Surface micromachining uses the planar fabrication techniques common to the microelectronic circuit fabrication industry to manufacture MEMS. The standard building-block process consists of depositing and photolithographically patterning alternate layers of controlled-stress polycrystalline silicon (polysilicon) and sacrificial silicon dioxide. As shown in Fig. 1, vias etched through the sacrificial layers provide anchor points between the mechanical layers and to the substrate. At the completion of the process, the sacrificial layers, as their name suggests, are selectively etched away in hydrofluoric acid (HF), which does not attack the polysilicon layers. The result is a construction system consisting of one layer of polysilicon which provides electrical interconnection and one or more independent layers of mechanical polysilicon which can be used to form mechanical elements ranging from a simple cantilevered beam to complex systems of springs, linkages, mass elements and joints. Because the entire process is based on standard integrated-circuit fabrication technology, hundreds to thousands of devices can be batch-fabricated on a single six-inch silicon substrate.

This basic process with a single-layer of mechanical polysilicon has been used to fabricate a myriad of devices which have been primarily sensors and sensor elements. The obvious extension of the process is to multiple levels of mechanical polysilicon layers with intervening layers of sacrificial films. However, this extension is not without cost, and careful consideration of the advantages to be gained against the investment required to develop the process must be made. Earlier work by Fan, Tai and Muller [7] illustrated that mechanical elements such as fixed-axle pin joints, self-constraining pin joints, and constrained sliders can be made with, and require, two layers of polysilicon. This work clearly indicated that the fabrication of movable, connected, mechanical elements are feasible with surface micromachining. However, complex, interactive mechanical devices require yet a third level of mechanical polysilicon to construct. This is easily seen by following Fig. 2a-c.

Typically, structures constructed with one level of polysilicon have restricted movement through elastic members attached to the substrate. Although the degree of mechanical complexity possible with a single level process is limited, it can nevertheless produce very useful and commercially viable devices, particularly in sensor applications.

One such example is Analog Device's surface-micromachined accelerometer [3], which is similar to the simple comb-drive pictured in Fig. 2a. Extension to a double-level process (Fig. 2b) begins to allow considerably greater mechanical design flexibility, particularly with regard to rotating elements. As seen in Fig. 2b, a free-spinning gear attached to the substrate with a free-spinning pin at some radius from its center can be produced. However, a third level of polysilicon is needed to couple energy to and from this gear. Fig. 2c illustrates this ability to interconnect elements with absolute, hard linkages for actuation purposes made possible through the use of three levels. Thus a comb drive (2a) capable of producing in-plane linear force and displacement can be coupled to the pin near the outer radius of the gear (2b) much like a piston is connected to a crankshaft by a connecting rod. Note also that any or all of the mechanical layers can be made electrically conductive, thus providing additional layers for electrical interconnect or electrodes. Although not clearly illustrated in Fig. 2, there is usually an additional polysilicon layer included in these processes. This polysilicon layer does not form mechanical elements, rather, it serves to form voltage reference planes and electrical interconnects. This film is not counted in the reference to single, double, and triple level processes. The full utility of the three-level process is fully exploited when we construct microengines with rotating interconnected elements.

Polysilicon Surface Micromachined MicroActuation

An often-cited motivation for developing MEMS is the potential extension to the advantages of small scale, which are currently available in electronic devices, to mechanical systems with moving parts. Several aspects of the advantages of MEMS, namely that micromechanical devices and systems are inherently smaller, lighter, faster, and possibly, more precise than their macro counterparts, are discussed elsewhere [8].

The fundamental building blocks of many systems consist of three basic functions: sensing, decision making, and actuation. The role of actuation is a critical part of most systems and will most certainly be required for any type of micro-machinery. Unfortunately, microactuation elements have thus far lagged in development compared to microsensor capabilities. This is principally due to the greater degree of mechanical complexity of the actuator elements and the additional issues of friction and wear.

There are several ways of organizing a discussion on micromechanics and microactuation. One is to draw distinctions by the means, or technique, of fabrication, e.g., polysilicon surface micromachining [9], silicon bulk micromachining [10], LIGA or LIGA-like micromachining [11], and others. A second approach would be by distinction

of the mechanism of actuation, for example, electrostatic, electromagnetic and magnetic, piezoelectric, shape memory alloy (SMA), thermoelectromechanical, to name a few. Generally, we can say that electrostatic-based actuators are most easily fabricated by batch methods with IC-type processes, while also being the most easily integrated with IC control. The other forms of actuation may be "better", i.e., greater force and/or displacement; however, they tend to require more specialized processing and are not as easily integrated into IC-type processing principally due to material compatibility issues.

It is obvious that we would like our actuators to provide large forces through large displacements at high power. The amount of force, displacement, or power available will depend on the type of actuator used. For example, there are actuators that are capable of delivering large forces but only through very limited displacements. Piezoelectric actuators tend to exhibit this type of characteristic [12]. Conversely, there are actuators that can move through large displacements but are only capable of delivering small forces. An electrostatic micromotor is an example of that type of actuator [13]. A thorough review and comparison of microactuation can be found in the work by Fujita and Gabriel [14]. Of the variety of actuation mechanism researched, the present discussion is limited to only those attempting to produce rotary motion that can be coupled to external structures to do work. In this regard, unlimited motion can be obtained and thus this type of actuator is often considered the most generic type.

History

Some of the earliest successful works on rotating output microactuators arose from a competition between University of California at Berkeley and Massachusetts Institute of Technology to produce the first rotating micromotor[15,16]. That early success spurred further investigation by many groups interested in exploiting micromotors. Unfortunately, the early designs were hindered by process-related and design-related constraints. Processing with a limited number of thin films precludes the ability to form an output shaft for power take-off. The alternative is to use the perimeter of the rotating element for power-take-off by gear teeth. This was hindered by the inclusion of the electrostatic actuation mechanism as part of the rotating element. These electrodes for actuation obscured access to the perimeter and prevented the formation of gear teeth on the perimeter. However, one point clearly demonstrated by these early micromotors was that our knowledge of friction at these dimensions was substantially inadequate. Further, these structures, being very small and having microscopically smooth surfaces, were susceptible to other phenomena such as surface tension. These phenomena lead to behavior more akin to adhesion than normal friction. The generic term of "stiction" is now often used to

describe this complex behavior and has been the primary stumbling block to getting micromotors to do usable work.

As with many endeavors, human ingenuity turned obstacle into useful attribute. And so, several researchers have turned the effects of stiction in their favor. For example, researchers at Case-Western Reserve University continued work on a particular design of electrostatic micromotor known as the wobble motor [17]. The basic principle of operation is easily understood by recalling the hula-hoop or by referring to the schematic illustrated in Fig. 3. As the rotor (hula-hoop) is "wobbled" about the bearing (your body), one also notices that the perimeter of the rotor is slowly rotating around the bearing. More precisely, the wobble motion is caused by the electrostatic attraction between the rotor and the stator electrodes as a voltage signal is stepped along the stator electrodes in a counterclockwise (CCW) direction. This can be visualized as a CCW rotation of the lobe formed by the rotor being pulled against the bearing. However, if the rotor does not slip along the bearing at the contact point, the path-length contacted along the inner perimeter of the rotor must match the path-length along the bearing surface. These two equal path-lengths are shown as the path-lengths from the current contact point CCW along the perimeters of the bearing and the rotor to the small circles drawn on each. When the contact point has moved from the left side to the right side, the two small circles must be coincident at contact. This implies that the rotor has rotated CCW. This rotation could be coupled to another geared mechanism if the hoop had external gear teeth. Such a motor with gear teeth on the outside perimeter and with the electrostatic actuation elements on its interior has been constructed although coupling of this gear to other geared elements has yet to be demonstrated. In this case, the micromotor overcomes rolling friction but needs sufficient resistance to sliding to operate. With no sliding friction this motor would have zero output torque. To date, surface micromachined wobble micromotors have been used to rotate optical mirrors plated onto their surface. A potential application is optical scanners. A second example where sliding friction is both overcome and put to work has been accomplished by researchers at UC - Berkeley. Their "vibromotor" relies on breaking static friction of rotating or sliding elements by using sequential impacts from a linear actuator[18]. These impacts are sufficient to overcome the static friction and load, while the friction is also sufficient to hold the actuated elements in the desired positions when not being impacted.

An alternative to these approaches is to start with a gear and provide a mechanical means to rotate it, i.e., analogous to pistons on a crankshaft or pedal arms on a bicycle crank. The difficulty with this approach is the added process complexity to create the

connections. Sandia has successfully adopted this approach in a variation of micromotor referred to as the microengine to produce a rotating output gear readily coupled to external geared mechanisms.

Microengine

More intricate actuation mechanisms require advanced mechanical designs coupled with additional levels of structural materials. The three-level process is fully utilized by the microengine shown in Fig. 4. Here, two linear electrostatic comb-drive actuators drive a set of linkages to a rotating output gear which engages the gear teeth on a large rotating shutter[6]. This output gear can be rotated by applying sinusoidal driving forces 90° out of phase with each other to each of the comb-drive actuators. This is analogous to the operation of two orthogonal pistons connected to a crankshaft. Operation of the small gear at rotational speeds in excess of 200,000 revolutions per minute has been demonstrated. The operational lifetime in air of these devices exceeds 8×10^8 revolutions.

An internal need to drive a large (1600 micrometer diameter) optical shutter is the first application of the Sandia microengine (shown in Fig. 4). Shutter rotational speeds of up to 4800 RPM have been obtained by taking into account inertial effects during the startup of the gears. This corresponds to a rotational speed of 150,000 RPM on the microengine output gear. A simple test consisting of mass loading on the surface of the large gears produced some surprising results. At a mass load of approximately 1 microgram, which corresponds to nearly 100 times the mass of the large gear itself, the microengine continues to operate smoothly.

Fig. 5 is a focused ion beam (FIB) micrograph of the output-gear and pin-joint cross-section. Shown in the FIB micrograph image are the cross-section details of the as-fabricated gear/link area just prior to the final release etch. A close-up scanning electron microscope (SEM) image of the released microengine in Fig. 6 shows details of the output gear and coupling elements.

Future Prospects

For many applications, it is imperative that after long idle times the microengine be able to startup and actuate without hesitation. On a different end of the spectrum, some applications require that the microengine run uninterrupted at high speed for months or even years. At several hundred thousand RPM this implies several tens or even hundreds of billions of rotations. Although the microengine produced some impressive initial results

in speed and longevity, considerable additional effort will be needed to meet such goals. It is not yet clear whether surface treatments, including film choices, will be able to solve both problems.

Although very important, surface effects are relatively insignificant in the macro counterparts to the microengine. At micro sizes, surface-to-volume ratio becomes ominously large and the study of surface science takes on a whole new dimension. Simply bathing the microengine in customary liquid lubricants such as silicone oil provides several expected benefits. Startup is more uniform and repeatable, and it is suspected that wear is reduced. Unfortunately, the large viscous drag forces caused by the liquid medium disallows high speed operation. Typically the speed of operation is reduced to tens or hundreds of RPM which, assuming the same lifetime of nearly a billion rotations as with no lubrication in air, effectively extends the lifetime indefinitely. So if low-speed operation in a liquid medium is desired, liquid lubrication is a realistic solution to the problem of reliable start-up and long wear.

If high-speed, long-duration operation is desired, dry lubricants must be used. Either methods of applying existing dry lubricants, or new classes of dry lubricants need to be developed. Application of dry lubricant to these devices is not a trivial task. The overall size of these microengines is on the order of the particle sizes in some dry lubricants. Delivery of or the coating of surfaces with micron or smaller gaps becomes problematic. Just as important as the lubricating properties of these surface treatments is their ability to passivate the surface of the microengine. They must keep the microengine from adhering to itself and becoming inoperable. These are very tough requirements for any surface treatment. Along these lines, talk of self-assembling molecular monolayers and surface coupling agents rumble on. There is a lot of new turf for the surface scientists to explore and the microengine is a proving ground for their ideas.

Complex devices, such as the microengine, are now ready to drive a great variety of devices with greater latitude than previously demonstrated. The recent literature, with some examples presented here, clearly indicates that microactuation is beginning to break free of many of its limitations and is starting to surface in several potential applications. In the near-term, various types of optical switching functions will be excellent candidates for application of these microactuators.

Potential applications in fluid pumping may also be relatively near-term. The liquid medium can provide both anti-sticking and lubrication benefits. Drug delivery and micro-chemical analysis would benefit from such small pumps. Further down the road, perhaps

high-speed rotational gyros for navigation will be possible once the issue of long wear in dry environments is solved. A definite possibility is that we may very well rethink our entire approach to shrinking down mechanical actuators as we continue to study the behavior of micromotors and microengines .

Acknowledgment

Figure Captions

Fig. 1 This example for surface micromachining is taken from the Sandia microengine [6]. Schematic cross-sections through essential elements of the gear and joints illustrate three stages of device completion.

        (a)   (b)   (c)

Fig. 2. a) Simple, yet very useful structures, particularly for sensor applications, can be fabricated using a single level of mechanical polysilicon. b) A double level process produces movable mechanical elements. However, connection to these structures is limited. Here a gear with a central hub attached to the substrate and a free-spinning pin along its radius is shown. Connection to the radial pin is not possible without a third layer of polysilicon. c) A triple level process allows the fabrication of complex, interconnected, interactive mechanisms with actuators. That is, the gear in Fig. 2b is now connected to a linkage element and can be actuated through that element by a force applied from a linear comb drive similar to the one shown in Fig. 2a.

Fig. 3. Schematic of an electrostatic wobble micromotor. By following the contact point as the rotor "wobbles" in a counterclockwise (CCW) direction, one can see that the two small circles on the rotor and bearing must meet when the rotor contacts the bearing at that point. Thus the rotor is rotating CCW also.

Fig. 4. Two sets of linear, electrostatic comb-drive actuators are linked to a 50 micrometer diameter drive gear. This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo.

Fig. 5. A FIB micrograph of the cross-section of the gear, joint, and link area just prior to the final HF release etch. Illustrated are the flanged hub attachment to the substrate and the upper link connected to the free-spinning pin joint in the gear. Typical polysilicon films thicknesses are of the order of 2 micrometers.

Fig. 6. SEM perspective view of the complete, released gear/link elements of the microengine. The gear shown has a diameter of approximately 50μm. The gear thickness is 2.5μm.

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POLY1 POLY2
POLY3
SILICON OXIDE

POLY1 + POLY2

POLY3

a) Undercut POLY1 to form the molds for the flanged joints using the POLY1 as its own mask.

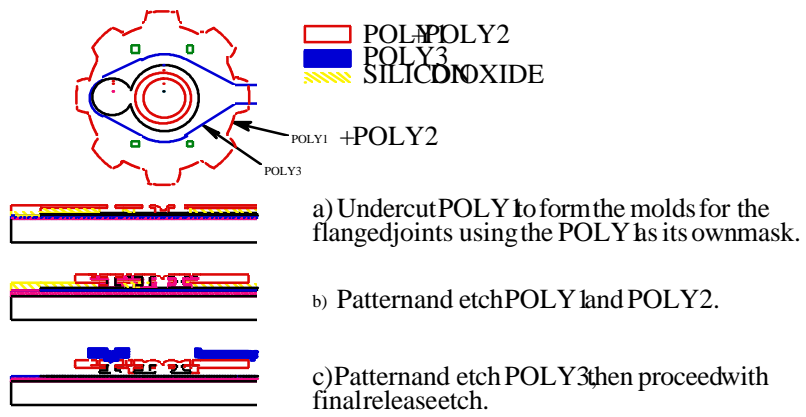b) Pattern and etch POLY1 and POLY2.
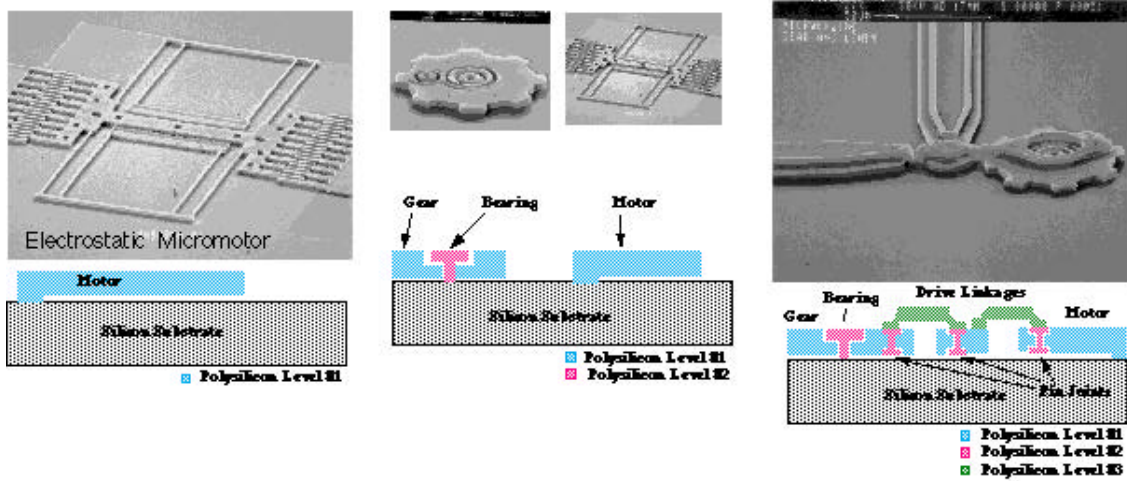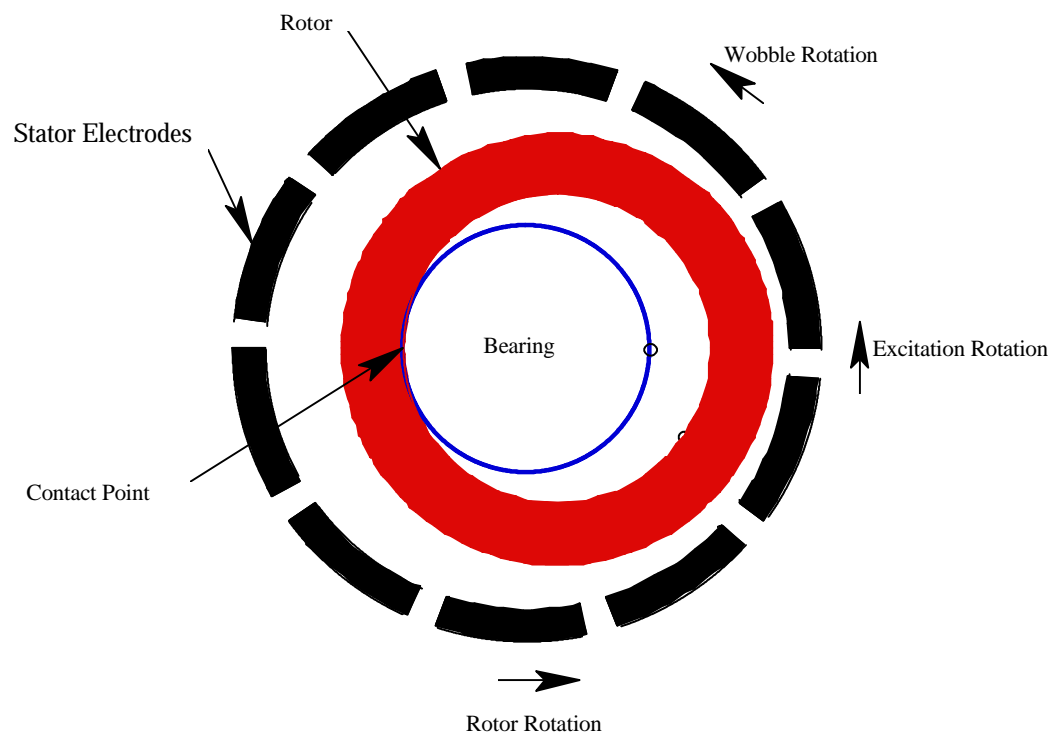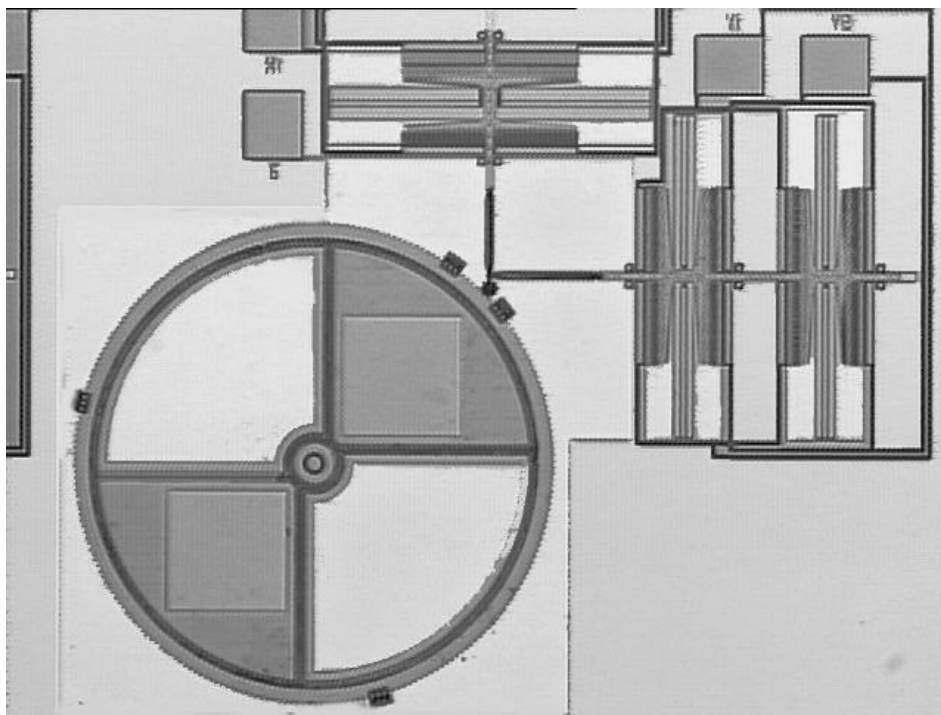
c) Pattern and etch POLY3 then proceed with final release etch.

Fig. 1

Fig. 2a-c

Fig. 3

Fig. 4

Fig. 5

Fig. 6